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Abstract

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Annual Technical Report

CONTROLLING MECHANISMS OF PULSATING INCINERATION PROCESSES

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Abstract

The goal of this study is to investigate the fundamental processes that control the performance of acoustically excited incineration systems. Cold flow tests performed under the first year of this program have demonstrated that natural acoustic mode oscillations, in the absence of net flow into or out of the volume, can be used to promote rapid mixing. Increased acoustic pressure amplitudes in the chamber were shown to increase the mixing rates. The dependence of the mixing rate on the mode of acoustic excitation was shown to be highly complex. Acoustic streaming also appears to have a significant influence upon flow and mixing patterns in the simulated incinerator. The effect of acoustic oscillations upon waste incineration was investigated by studying the effect of acoustic oscillations upon dry ice sublimation. This study showed that the presence of pulsations enhanced the sublimation process, which strongly suggests that they would also enhance the process of burning solid wastes. Preparations are underway to investigate the effects of acoustics on the combustion of waste surrogates.

Introduction

The objective of incineration is to completely burn the combustible portion of the waste material without emitting hazardous substances into the environment. The incineration of solid wastes generally proceeds through a number of individual processes, including heating of the waste, evaporation of its water content, devolatilization, pyrolysis, mixing of gaseous fuel and oxidizer, ignition, and combustion. These processes do not necessarily occur in this order, and when liquid or gaseous wastes are incinerated, some of these processes are eliminated. In order to obtain complete incineration within the limited volume of a compact incinerator, the rates of all the above listed processes must be high. At present, high gas phase mixing rates are generally attained by providing the incinerator with an air flow rate that is considerably higher than that required for a stoichiometric combustion process. This reduces the global fuel/air ratio within the incinerator, resulting in lower reaction temperatures. Thus, while high air flow rates promote faster gas phase mixing and increase the rate of convective heat transfer between the gas phase and the solid waste, the effect is compensated by lower temperatures and the resulting reduction in waste heating rates and slower chemical kinetics.

The investigation and development of techniques that will enhance the rates of various transport processes are crucial to the development of incinerators that are more compact, more efficient and emit less pollutants than state of the art incineration systems. Recent investigations have demonstrated that the presence of acoustic oscillations and flow pulsations can increase the rates of transport processes. Patera et. al.,[1,2] for example, have shown that mixing and heat transfer rates in laminar flow in a channel can be considerably increased by oscillating the flow rate into the channel at a frequency at which the flow's shear layer is unstable. While there is considerable evidence that mass[3] and heat[4,5,6] transfer rates are increased by acoustic oscillations, the precise mechanisms responsible for these increases are not entirely understood. Strong evidence[4,7] suggests that the increased transport rates are due to the excitation of turbulence and vortical structures by the acoustic oscillations. In a study by Vermeulen et al.,[8] flow oscillations were shown to reduce flow stratification and improve mixing. This was revealed by the elimination of localized pockets of high temperature gas, or "hot spots", at the exit plane of a gas turbine combustor, which can damage turbine blades downstream of the combustor. The capability to reduce or eliminate this type of local stratification is of practical importance in incinerators because non-uniform loading of waste materials leads to fuel rich regions in the incinerator, which can result in the emission of "puffs" consisting of soot, CO, and unburned hydrocarbons. Also, "hot spots" may be the cause of increased thermal nitrogen oxide production by the Zeldovich mechanism.

Results of several investigations of pulse combustors suggest that when combustion occurs in an oscillatory flow field, the combustion time is reduced and combustion efficiencies are

increased with respect to combustion in a steady flow field. For example, Lyman[9] showed that pulsations increased the burning rates of individual coal particles, and Zinn et al.[10] found that unpulverized coal nuggets can be burned in a Rijke type pulse combustor with high combustion efficiency while utilizing little excess air. Bai et al.[11] showed that heavy fuel oils, which are generally difficult to burn, can be burned with high combustion efficiencies in a pulse combustor specifically designed for this purpose.

A recent study supported by the EPA investigated the effects of pulsations upon the incineration process.[12] In the study, a tunable pulse combustor was retrofitted to an existing EPA rotary kiln incinerator simulator and used to excite large amplitude acoustic mode oscillations within the incinerator. Toluene and polyethylene were burned as surrogates for hazardous and municipal wastes, respectively. Pulsations were shown to reduce the magnitude of "puffs" and soot emissions. Interestingly, reductions in soot emissions observed when burning toluene with pulsations were, in some cases, accompanied by increased levels of CO and hydrocarbon emissions. In contrast, when polyethylene was burned in the presence of pulsations, the emissions of soot, CO, and hydrocarbons were all reduced. In both cases, the pulsations reduced the O_2 concentrations in the exhaust to very low levels, indicating that the pulsations improved the utilization of available oxygen in the incineration process.

Research Accomplishments

The objective of the present study is to investigate the mechanisms through which pulsations affect the incineration process in order to obtain information that will aid the development of an efficient and compact incinerator for ship-board use. Specifically, the effects of acoustics on the mixing rates, flow characteristics, burning rates of solid and liquid wastes, and smoke, NO_X, CO, and unburned hydrocarbon emissions are being investigated in simulated incinerators.

In the first phase of this study, cold flow tests were performed to investigate the effects of acoustics upon transport phenomena and flow conditions in a simulated incinerator. In an effort to better understand the increase in mixing rates due to oscillations, the characteristics of the mixing produced by high amplitude, resonant acoustic oscillations in a rectangular cavity with no mean flow were investigated. In such a setup, the observed mixing can often be associated with acoustic streaming.[13] It is well known that periodic sound sources can generate non-periodic motions in the medium.[14-16] In his paper on streaming and vorticity generated by sound waves,[14] Eckart showed that circulation necessarily follows as part of the solution to the wave equation when one accounts for the viscosity and second order terms. This study aims to shed some light on the role that this phenomenon plays in the increased rate of transport processes observed in pulsating flow fields.

A schematic of the experimental setup used in the mixing rate studies is shown in Fig. 1. The setup consists of a rectangular wooden box with one acrylic side. The cavity is 27" x 8" x 5" (68.6cm x 20.3cm x 12.7cm). These dimensions were chosen to prevent redundant natural frequencies over the range of interest. Four University Sound 75 watt compression type acoustic drivers were used to excite standing acoustic waves in the box. The drivers were mounted on the ends and bottom of the setup, which allowed longitudinal, transverse, and multidimensional acoustic modes to be excited. Sound pressure levels as high as 158 dB rms can be driven for certain modes. In the report, the natural acoustic modes are identified by the longitudinal mode number and the mode number in the 8" direction (referred to as the transverse mode). Oscillations in the 5" direction were not used in this study, and so the mode numbers in this direction are assumed to be zero. For example, by this convention, the (1,0) mode refers to the fundamental longitudinal mode and the (2,0) mode refers to the second longitudinal mode. These modes are shown in Fig. 2. The (1,1) mode and the (3,1) mode, shown in Fig. 3, refer to the two dimensional modes which are combinations of the first longitudinal and the first transverse modes and the third longitudinal and the first transverse modes, respectively.

The acoustic driving in the setup can be achieved by either open or a closed loop operation. In open loop operation, a signal to the drivers is provided by a function generator at a chosen frequency. In closed loop active control operation, the acoustic pressure signal in the chamber, measured using a Kistler piezoelectric pressure transducer, is amplified, phase-shifted, and fed back into the acoustic drivers. By adjusting the gain, phase-shift, position of the pressure probe and the combination of utilized drivers, the system can be tuned to resonate in various acoustic modes. While open loop operation is advantageous in its simplicity, closed loop active control provides the benefit of finding and 'locking on' to various resonant modes. This benefit is quite useful in combustion systems, in which slight variations in the temperature can cause the resonant frequencies to drift.

The rate of mixing between smoke-laden air and smoke-free air in the cavity was measured under various modes of acoustic excitation. Digital imaging was used to record and quantify the mixing process on a plane illuminated by a light sheet (see Fig. 1). The light sheet was created with an argon ion laser and the necessary optics, and a Kodak EctaPro intensified CCD camera was used to record the Mie scattering from the smoke particles. Figure 4 is a schematic showing the instrumentation used. A removable partition in the middle of the setup was used to establish an initial condition for the smoke. Before each test, the partition was inserted and half of the box was filled with smoke (i.e., one side of the partition). The smoke in this half of the box was well-mixed and allowed to become quiescent. The partition was then removed, the camera was triggered, and oscillations were excited in the box. The camera recorded 50 frames per second

and had a 3600 frame memory buffer. Frames are then downloaded to a computer for storage and analysis.

A sequence of frames from a typical test is shown in Fig.5. The first frame shows the initially separate smoke and air in the box just after the partition has been removed and as the resonant acoustic driving is initiated. As time increases, mixing proceeds from large scale to small scale until, as seen in the final frame, mixing is complete on the resolution scale of the camera. Figure 6 shows the histograms of the frames as they evolve in time. At 0 seconds, the histogram is bimodal, because half the box is filled with smoke and scatters light strongly while the other half has no smoke appears dark. As the smoke and air mix, the regions of light and dark diminish as the number of pixels that measure medium intensity increases.

The analysis technique used to quantify the mixing observed in this study is based upon a method employed by Liscinsky et al.[17,18] In this technique, a parameter called the "spatial unmixedness" (*Us*) is used to provide a measure of the degree to which a population is mixed. In the present study, a definition of *Us* that is somewhat modified from that given by Liscinsky et al[17,18] was used, and is defined as

$$U_s = \frac{\mathrm{Var}(I)}{\mathrm{Var}_{t=0}(I)} \tag{1}$$

where

$\mathrm{Var}(I)$	=	$\frac{1}{m}\sum_{n=1}^{m}\left(I_n - I_{ave}\right)^2$
	=	spatial variance of pixel intensity
$\mathrm{Var}_{t=0}(I)$	=	spatial variance of the t = 0 frame
m	=	number of pixels / frame
I_n	=	intensity of the n^{th} pixel
I_{ave}	=	$\frac{1}{m}\sum_{n=1}^{m} I_n$
	=	average pixel intensity of frame

Stated simply, the "spatial unmixedness" *Us* is defined here as the variance of the intensity of the frame at time t normalized by the variance of the frame at $t = 0$. Normalization allows comparisons to be made between runs where the total amount of smoke added to the box or the intensity of the light sheet may not be exactly the same. The value of *Us* at t=0 is, from Eq.1, define as 1. As the image becomes increasingly mixed, *Us* approaches 0.

A typical example of the change of *Us* over time is shown in Fig. 7. In this test, the fundamental longitudinal mode (f = 250 Hz) was driven in the chamber by the two end mounted drivers (operating 180^0 out of phase) at 144 dB rms. Note that local increases (just after 20 seconds, for example) in the value of *Us* do not violate the second law of thermodynamics, because the measured *Us* represents only a planer slice of the three dimensional volume. While the overall volume cannot "unmix", measured increases in the value of *Us* represent a localized effect of the three dimensional mixing process. As the mixing approaches completion, the length scale of the mixing decreases, and the maximum possible fluctuation in *Us* due to three dimensional effects decreases proportionally. The times at which *Us* has decreased to values of e^{-n} are shown in the figure. At $\tau\left(e^{-4}\right)$, Us has decreased to a value of 1.83% of its original value. In this study, this was considered to be the point at which the smoke and air were fully mixed. An example of the change of *Us* over time for a test without sound is shown in Fig. 8. In this case, the mixing is driven mainly by convection due to the buoyancy of the smoke (which is slightly warmer than the air temperature) and, to a lesser extent, diffusion.

Experiments were performed to determine the effect of the amplitude of the oscillation upon the characteristic mixing time (or, inversely, the mixing rate) of the smoke and air in the chamber. Because of the chaotic nature of the mixing process, each test was repeated 6 times to provide better statistical accuracy. Figure 9 shows the measured dependence of the characteristic mixing time (defined here as the time for *Us* to decrease to a value of e^{-4}) upon the rms acoustic amplitude. The diagram of the experimental setup in the figure shows the initial configuration of the tests, the drivers that were used to excite the oscillation, and the acoustic mode, which in this case is the 1st longitudinal 0th transverse mode, or, in other words, the fundamental longitudinal mode.

The figure shows that the characteristic mixing time decreases as the amplitude of the acoustic oscillations increases. The curve though the data is a least-squares fit of the equation $\tau = \frac{c}{p^{\nu}}$, where p is the amplitude of the pressure oscillations and c and ν are determined by the curve fitting procedure. A plot of the average mixing rate, defined as $1/\tau$, is shown in Fig. 10.

Tests were performed to determine the dependence of the mixing rate upon the mode of the excited acoustic oscillations. The results of one such series of tests are shown in Fig. 11. In these tests, acoustic oscillations at different longitudinal modes were driven in the box at an rms amplitude of 152dB using 2 drivers mounted at opposite ends. The drivers were operated 180^0 out of phase for odd modes and in phase for even modes to provide efficient driving. The average mixing rates of the 4th and 6th longitudinal mode could not be calculated, because *Us* did not

decrease to a value of e^{-4} during the 72 seconds of storage time available with the camera, indicating that the average mixing rate in both cases is below $0.014s^{-1}$.

This graph shows an interesting result. In this configuration, driving of even acoustic modes appears to produce slower mixing the driving of odd acoustic modes. This can be attributed to the presence of an acoustic velocity antinode at the original interface plane between the smoke and air for odd modes of oscillation, and an acoustic velocity node at this interface plane when even modes are excited. It appears that an acoustic displacement at the interface aids in starting the mixing process.

Further tests were conducted using non-symmetrical driver configurations in order to determine whether the mixing rate depends not only is the mode of acoustic oscillation but also on the placement of the drivers. The results of two experiments using different non-symmetrical driver placements are shown in Fig. 12. In neither of these cases are the mixing rates for even acoustic modes noticeably less than for the odd modes. In fact, in both cases, the mixing provided by the (6,0) mode is quite fast. The marked differences between the results of the three experiments shown in Figs. 11 and 12 demonstrate that the mixing rate of the smoke and air in the box depends strongly on the placement of the drivers. This result suggests that the mixing is influenced by three dimensional acoustic processes in the vicinity of the drivers and acoustic streaming.

Experiments were also performed to investigate the effects of transverse and multi-dimensional mode excitation upon the mixing rates. Mixing rates measured for a number of transverse and two dimensional modes are plotted in Fig. 13. The tests were performed using the two bottom mounted acoustic drivers to excite oscillations of 148dB rms amplitude in the chamber. The figure shows that while the second pure transverse mode produces a slower mixing rate than the fundamental transverse mode oscillation, this trend is reversed for two dimensional modes where driving the (n,2) combined mode results in consistently faster mixing than the (n,1) mode.

In order to investigate the influence of the driver position upon the average mixing time, flow visualization was performed and a number of velocity measurements were made using an Aerometrics LDV system. Preliminary measurements in the vicinity of an acoustic driver showed that the oscillating driver was inducing a mean flow radially inward along the wall and outward along the axis of the driver, as shown in Fig. 14, that was clearly visible in flow visualization videos. This "acoustic jetting" is similar to the streaming patterns observe by Ingard[16] in a study of the impedance of a circular orifice. Tests were performed to determine the nature of the streaming from the drivers. Figure 15 shows velocity measurements for a configuration in which one end mounted driver was used to excite the (3,0) mode. The component along the axis of the driver (which lies at the center of the end wall) of the mean and acoustic velocity are plotted in

the figure. Some distortion of the standing wave is observed in the vicinity of the driver. This is expected, however, due to the impedance mismatch between the driver, which has a relativel) high acoustic velocity, and the hard wall, which presents a boundary condition of a practically acoustic velocity. The induced mean jet is shown to extend several inches out from the driver.

In the second phase of this study, which is currently underway, cold flow tests are being performed to investigate the effects of acoustics upon transport phenomena and flow conditions in an experimental setup with a mean flow of air representing the flow of oxidizer into an incinerator. A schematic of the setup used in this phase of the study is shown in Fig. 16a. The cavity dimensions of the setup are 27" x 8" x 5" (68.6cm x 20.3cm x 12.7cm), the same as those of the setup without mean flow. In this facility, four 100 watt Atlas compression type acoustic drivers are mounted along one wall to provide driving of longitudinal, transverse, and two dimensional modes. The previously described systems for driving oscillations in either open or closed loop operation are available.

Flow visualization studies using Mie scattering from aluminum dioxide particles seeded in the mean flow revealed that when driving high amplitude oscillations (e.g., above 150 dB), the acoustic jetting from the drivers was often of large enough to disrupt the in-flowing air. To reduce the effect of the drivers upon future tests, the acoustic oscillations in the chamber are now, in general, excited using only the two drivers in the downstream ends of the box.

The effect of acoustic oscillations upon waste incineration was investigated by studying the effect of acoustic oscillations upon dry ice (solid phase CO_2) sublimation. Dry ice was chosen as a waste surrogate for cold flow testing for two reasons. First, the sublimation of dry ice bears a similarity to the pyrolysis of solid fuels. Second, due to the presence of a small amount of water (generally less than 1%) trapped in the dry ice during the manufacturing process, it produces a visible "fog" as it sublimes.

Preliminary tests, configured as shown in Fig. 16b, have been performed to determine if the presence of transverse oscillations in the simulated incinerator can enhance the sublimation rate of dry ice. These tests were performed with a mean air jet velocity of 0.7 m/s. In these tests, pieces of dry ice were weighed and placed in the box in the path of the incoming, mean, air jet, as shown in the figure. After a set test time, the dry ice was removed and the percentage by which the mass changed was measured. The results of these tests ate tabulated in Table 1. The errors associated with this method are large because while the initial weight was kept constant from run to run, the initial surface area of the dry ice could not be kept constant. The results show, however, that in all but one instance that the presence of oscillations enhanced the rate of sublimation. More accurate testing methods and tests using acetone as a liquid waste surrogate are currently underway.

Run Time	No Sound	142 dB	150 dB	152 dB
5 min	22.1%	22.2%		
10 min	46.5%	42.9%		
10 min	40.4%		46.7%	52.1%
10 min	44.2%			51.1%
10 min	45.7%			58.1%
10 min	40.0%			45.4%

Table 1. Percent change in mass of dry ice for different amplitudes of acoustic excitation.

Facilities and test preparations for the third phase of this study, testing with combustion, are currently being completed. In this simulated incineration facility, acetone and other waste surrogates will be burned in the presence of transverse and multi-dimensional mode acoustic excitation. Initial tests planned for this facility are to measure the effects of acoustic oscillations of the soot, NOx, CO and UHC levels present in the incinerator exhaust.

Summary and Conclusions

The objective of the present study is to investigate the mechanisms through which pulsations affect the incineration process in order to obtain information that will aid the development of an efficient and compact incinerator for ship-board use. Specifically, the effects of acoustics on the mixing rates, flow characteristics, burning rates of solid and liquid wastes, and smoke, NO_X, CO, and unburned hydrocarbon emissions are being investigated in simulated incinerators.

Experimental facilities were developed in which the effects of high amplitude, resonant, acoustic oscillations upon various processes relevant to incineration could be investigated. The development of a closed loop active control system ensures that the simulated incinerator can be driven at a resonant frequency, regardless of small temperature variations during operation. This reduces the severity of the change in amplitude that would otherwise occur if the temperature drifted, and can assure maximum amplitude for a given driving power.

In the first phase of this study, cold flow tests were performed to investigate the increase in mixing rates due to high amplitude, resonant acoustic oscillations. The characteristics of the mixing produced by acoustic oscillations were investigated in a rectangular cavity with no mean flow. The effect of acoustic excitation upon the rate of mixing was measured, and increases in the sound pressure level in the chamber were shown to rapidly increase the mixing rate of smoke and air in the chamber. The mixing rate was shown to have a complex dependence on the mode of acoustic excitation. Acoustic streaming appears to have a significant influence upon flow and

mixing patterns in the simulated incinerator, because the mixing rate of the smoke and air in the box depends strongly on the placement of the drivers. In order to investigate the influence of the driver position upon the average mixing rate, flow visualization was performed and a number of velocity measurements were made, which revealed patterns of mean flow induced by the piston action of the drivers.

The incineration process of solid wastes can be enhanced by increasing the heat transfer rate to the waste and the pyrolysis rate of the fuel. The effect of acoustic oscillations upon waste incineration was investigated by studying the effect of acoustic oscillations upon dry ice sublimation. Results of preliminary studies suggest that acoustic excitation enhances the sublimation rate of dry ice in the simulated incinerator, which strongly suggests that they would also enhance the process of burning solid wastes. However, due to large uncertainties associated with the measurement technique, more accurate studies are underway to provide more reliable evidence. Studies involving acetone as a liquid waste surrogate are also planned.

Work Statement For Second Year

Task 1: Complete cold flow studies including investigations of acoustically excited flow field near the simulated waste, but away from the driver locations.

Task 2: Complete design and construction of the experimental facility to be used in the combustion experiments. Set up diagnostics including planer laser fluorescence.

Task 3: Investigate the effect of acoustic excitation on the rate of evaporation and combustion of a liquid surrogate waste.

Task 4: Investigate the effect of acoustic excitations on the level of soot, NOx, CO, and unburned hydrocarbons in the exhaust of the simulated incinerator while burning solid surrogate wastes.

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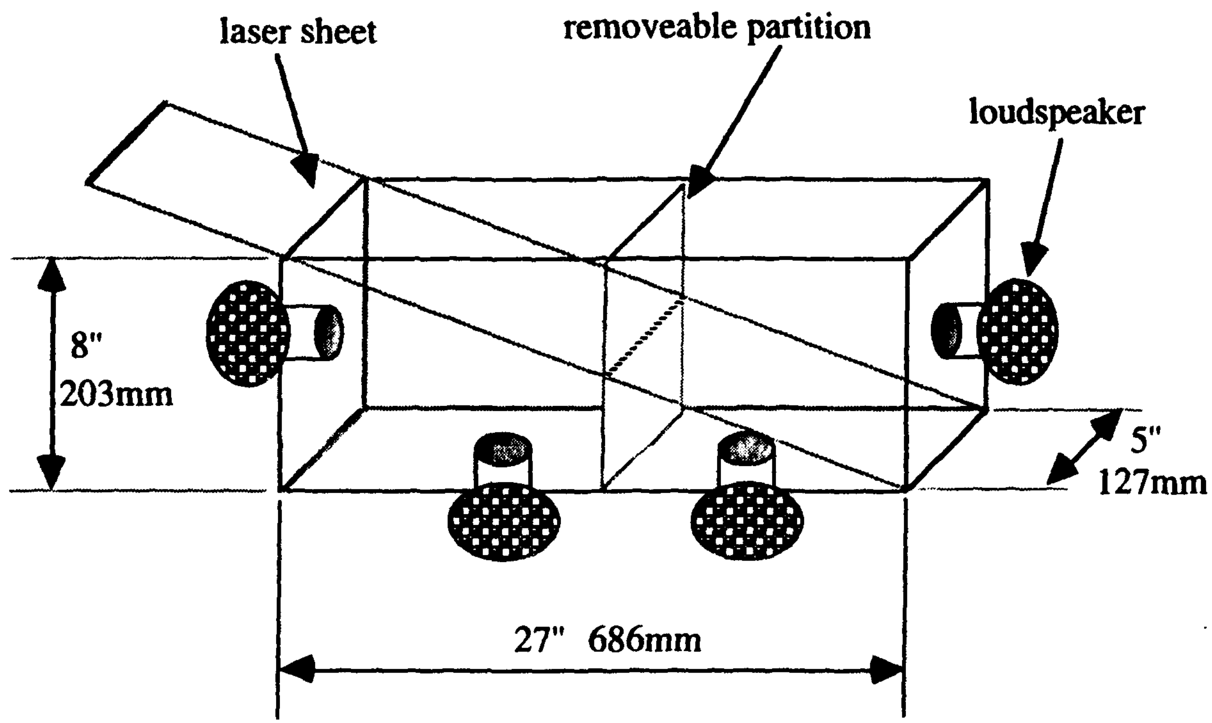


Figure 1. Schematic of the smoke-air mixing box

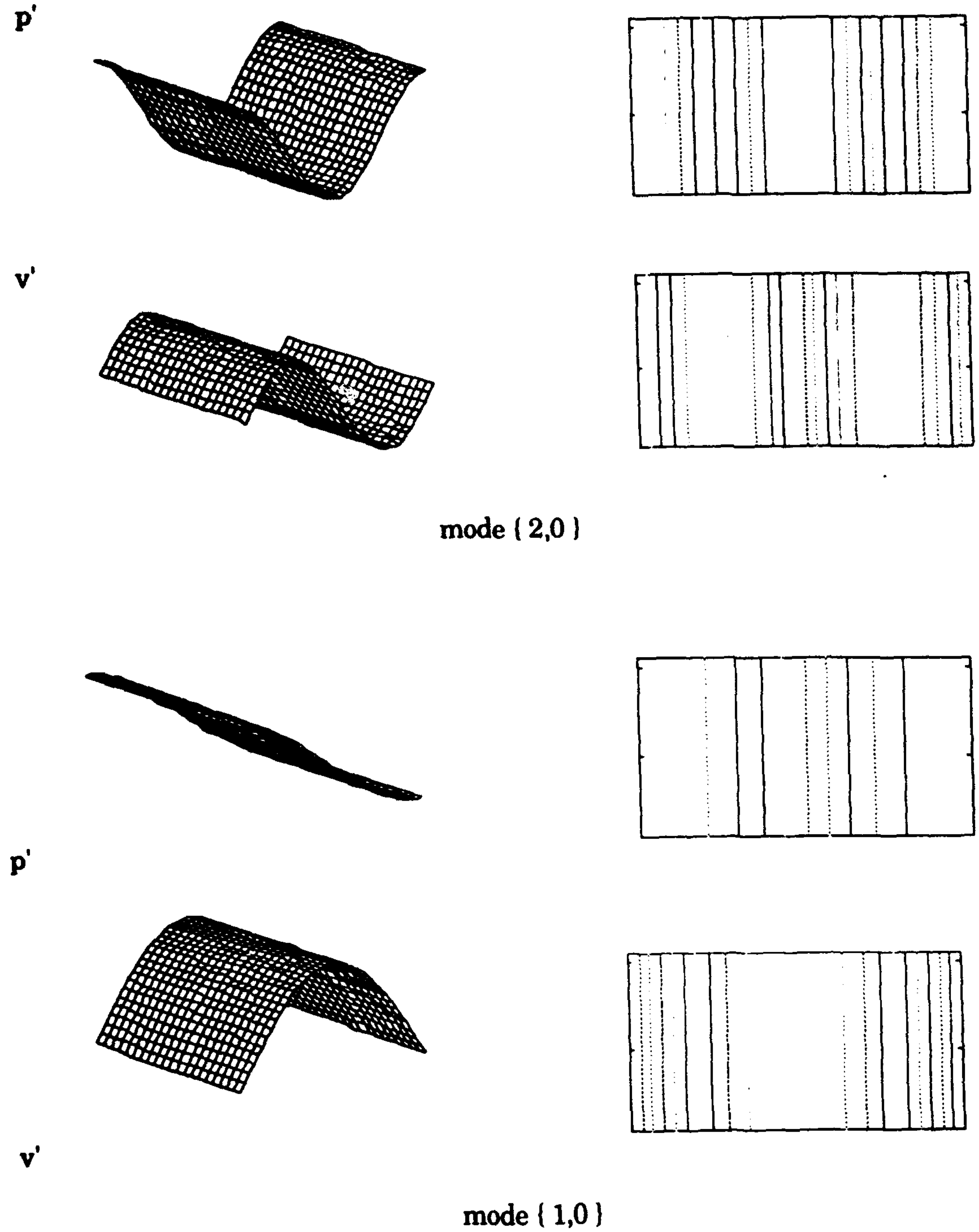
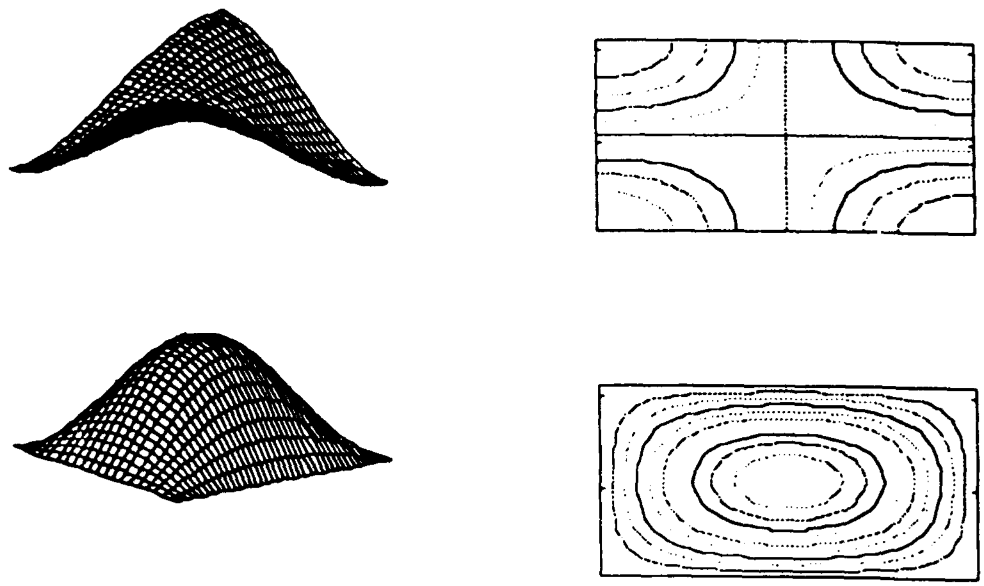


Figure 2 The acoustic pressure and velocity amplitudes of the first and second longitudinal modes



p'

v'

mode { 1,1 }

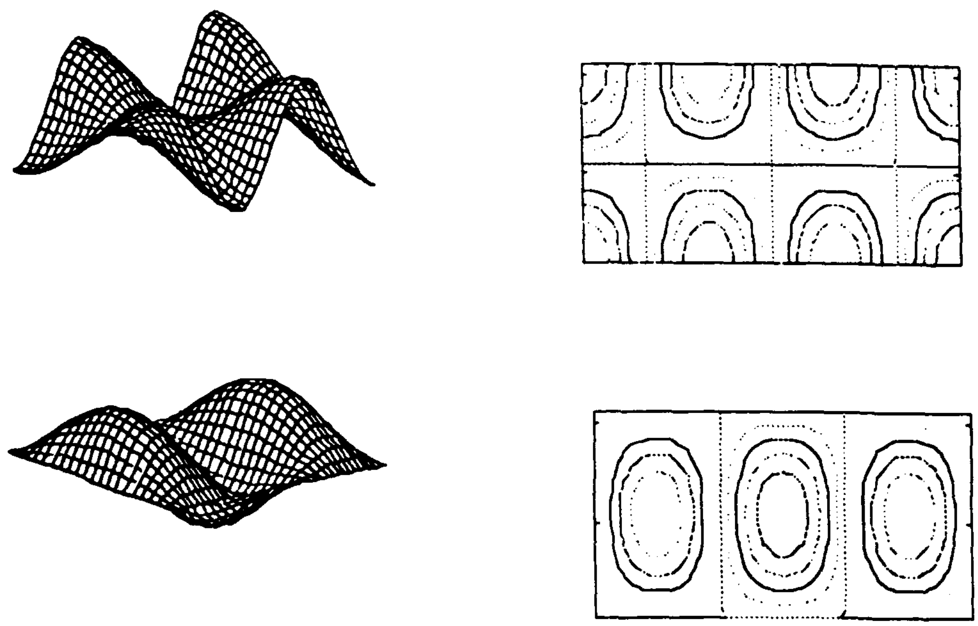


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Figure 3. The acoustic pressure and velocity amplitudes of typical two-dimensional modes

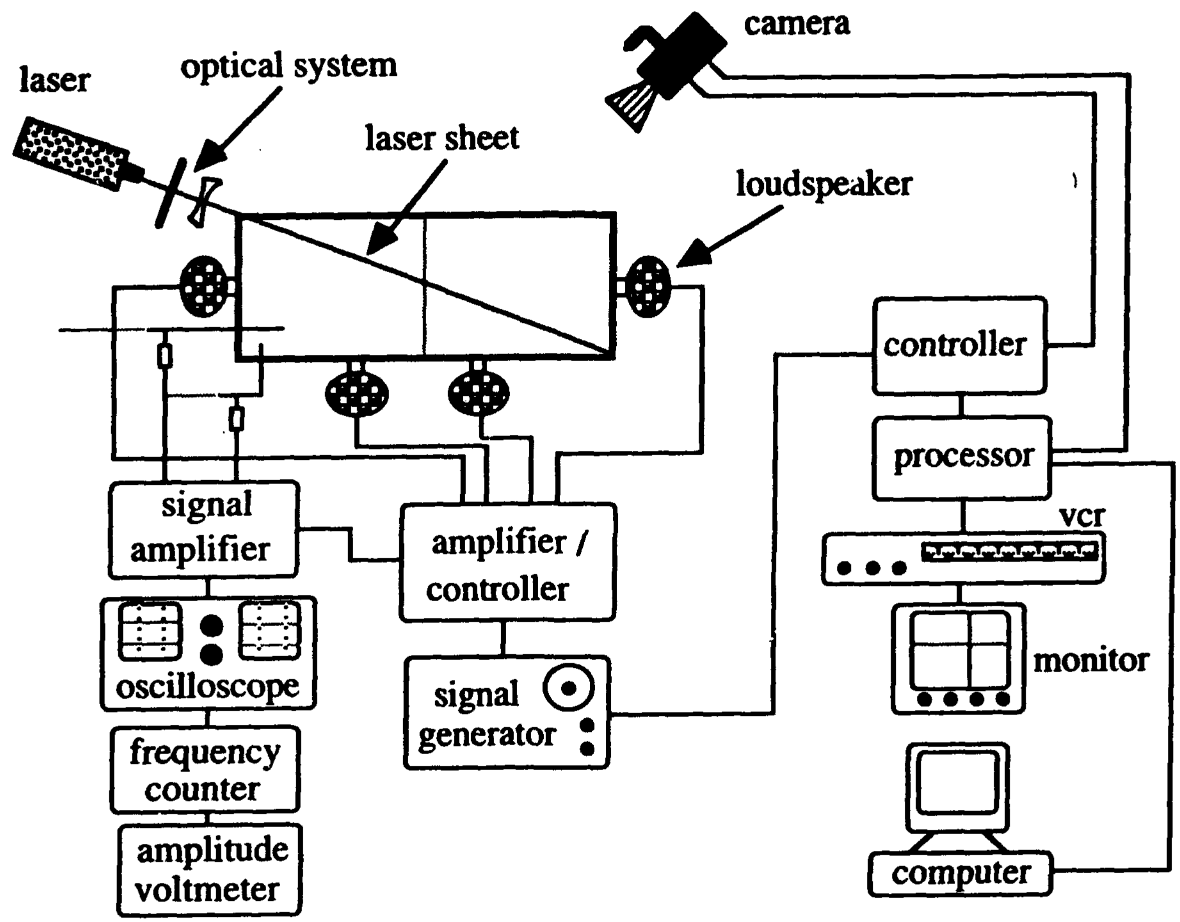


Figure 4. Schematic of experimental system

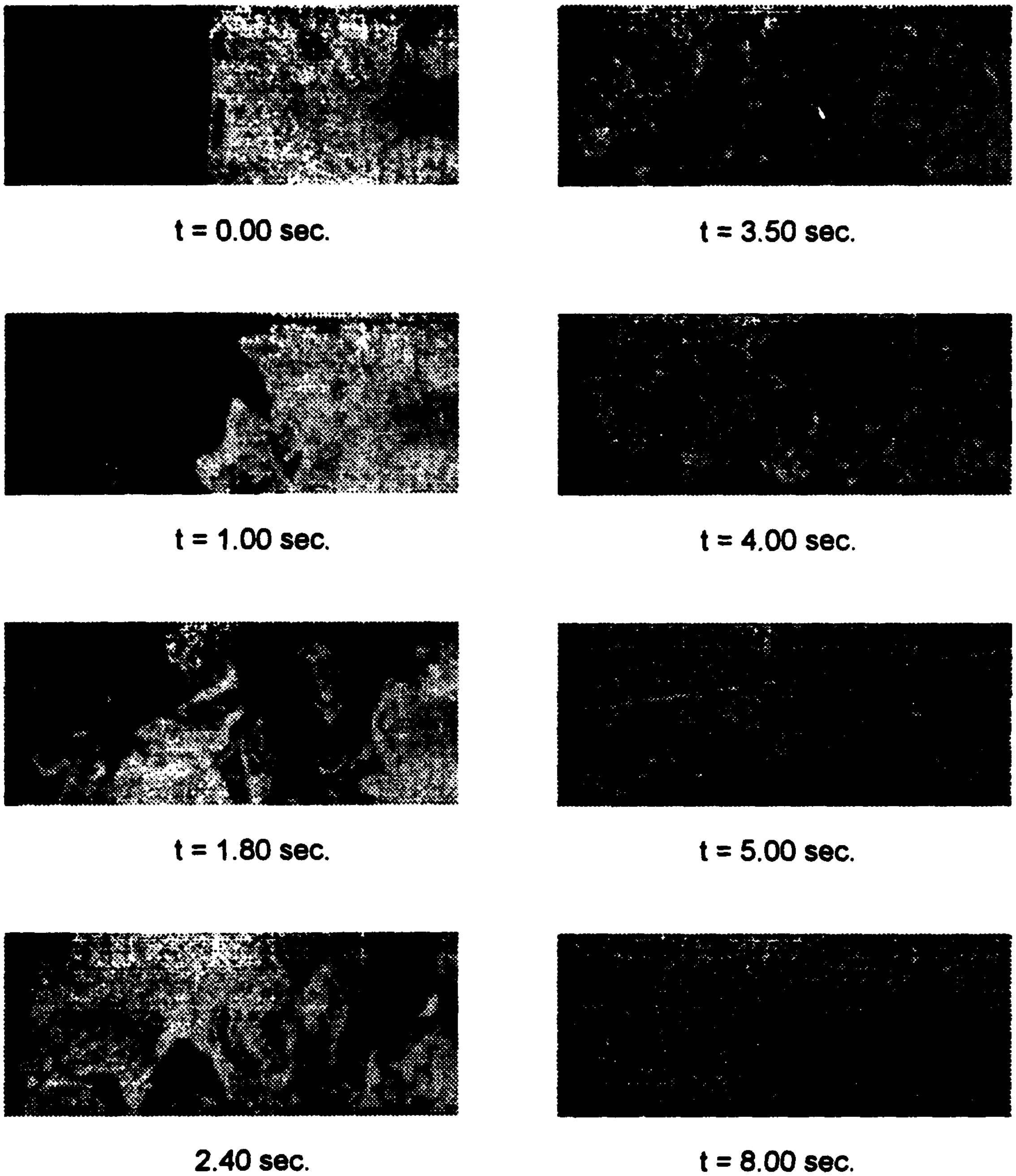


Figure 5. Sequence of images from a typical test showing the mixing of smoke and air by the excitation of acoustic oscillations.

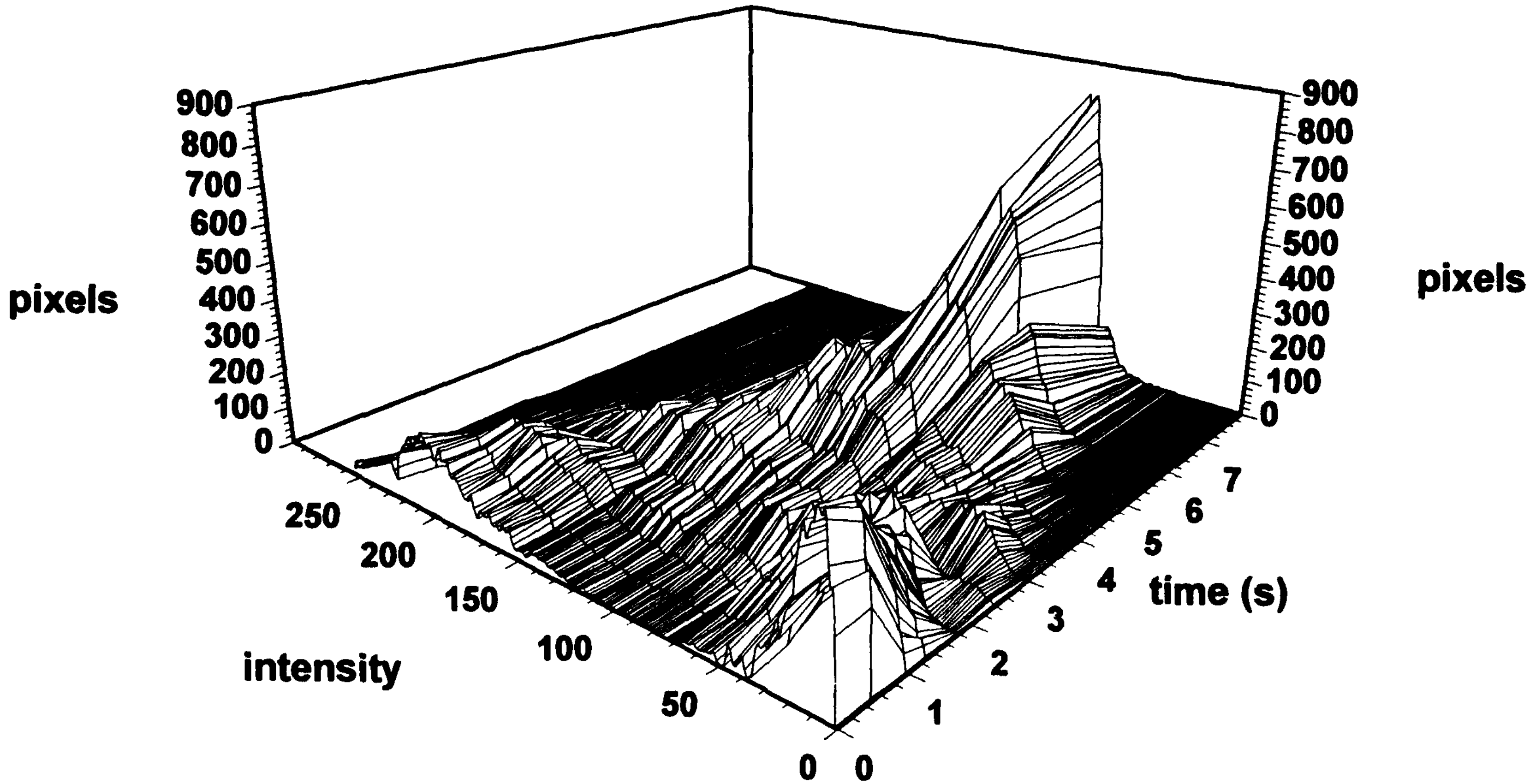


Figure 6. Time evolution of the intensity histograms of a sequence of images from a typical acoustic mixing experiment.

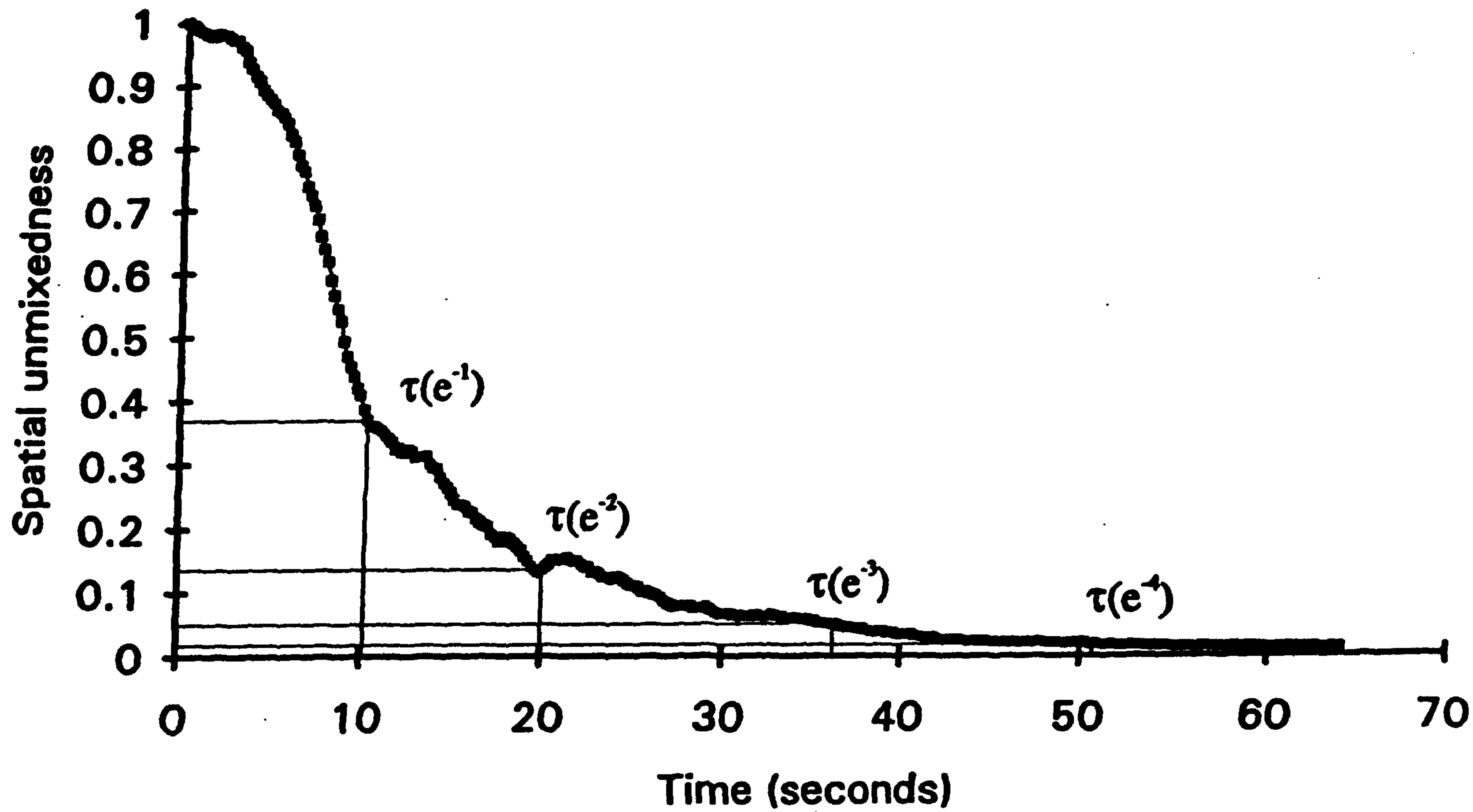


Figure 7. Spatial unmixedness vs Time

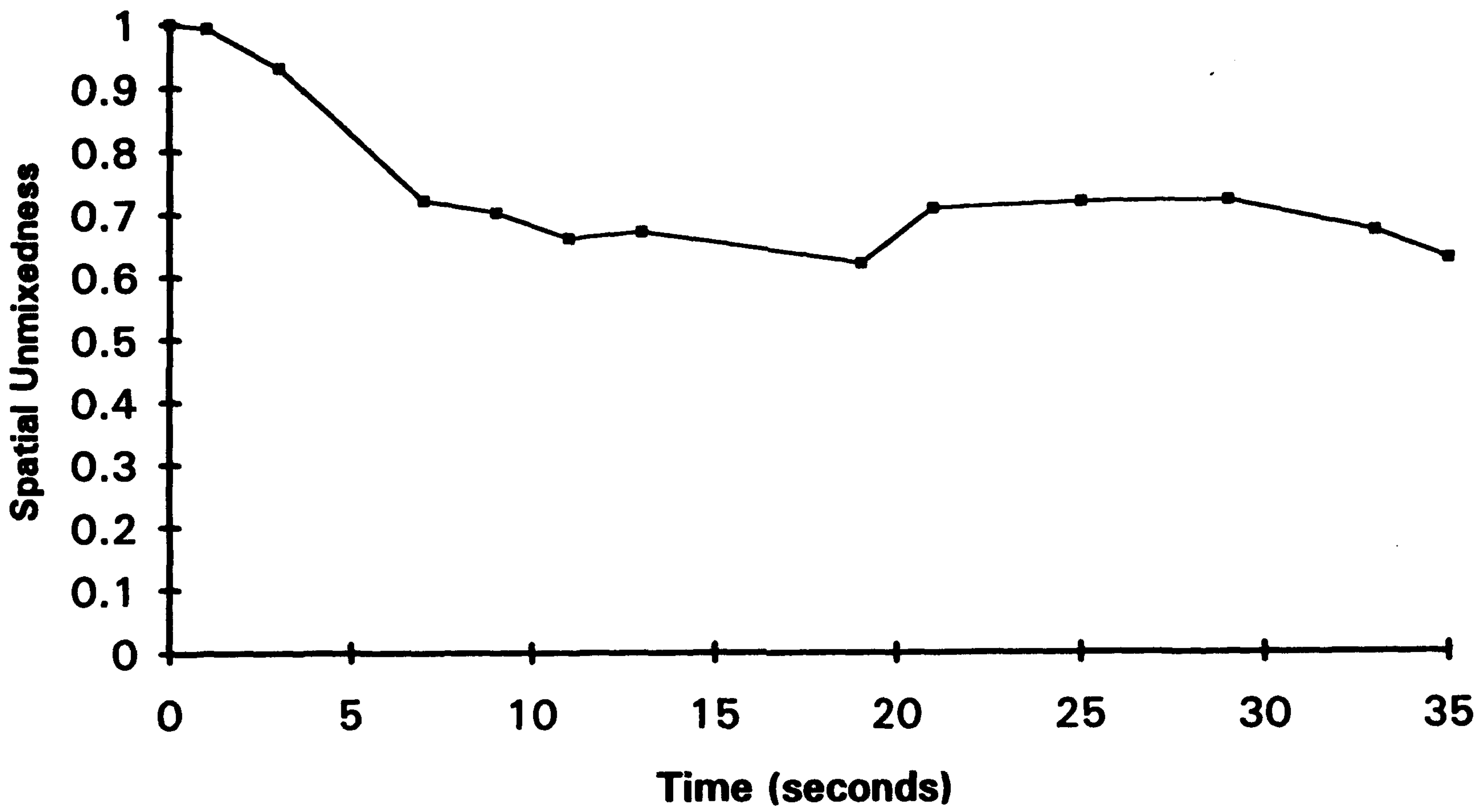


Figure 8. History of the spatial unmixedness in the absence of acoustic oscillations.

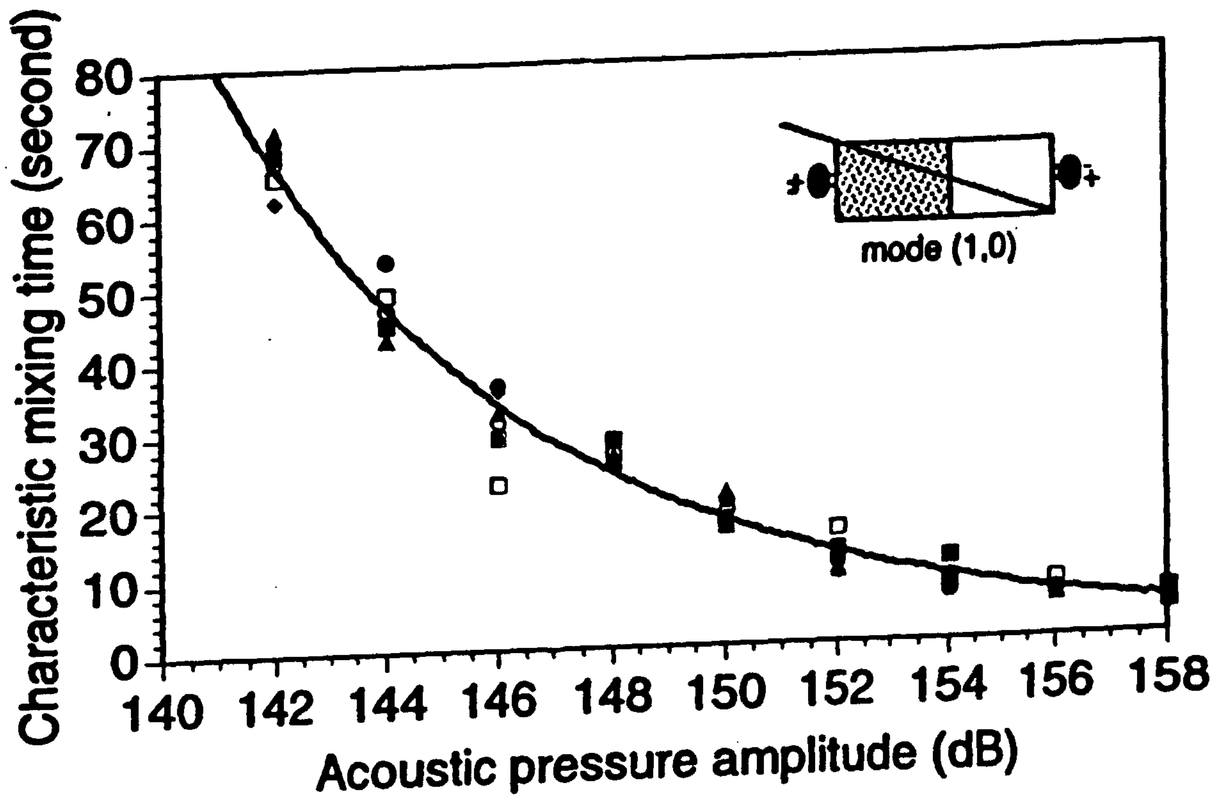


Figure 9. Characteristic mixing time vs acoustic pressure amplitude

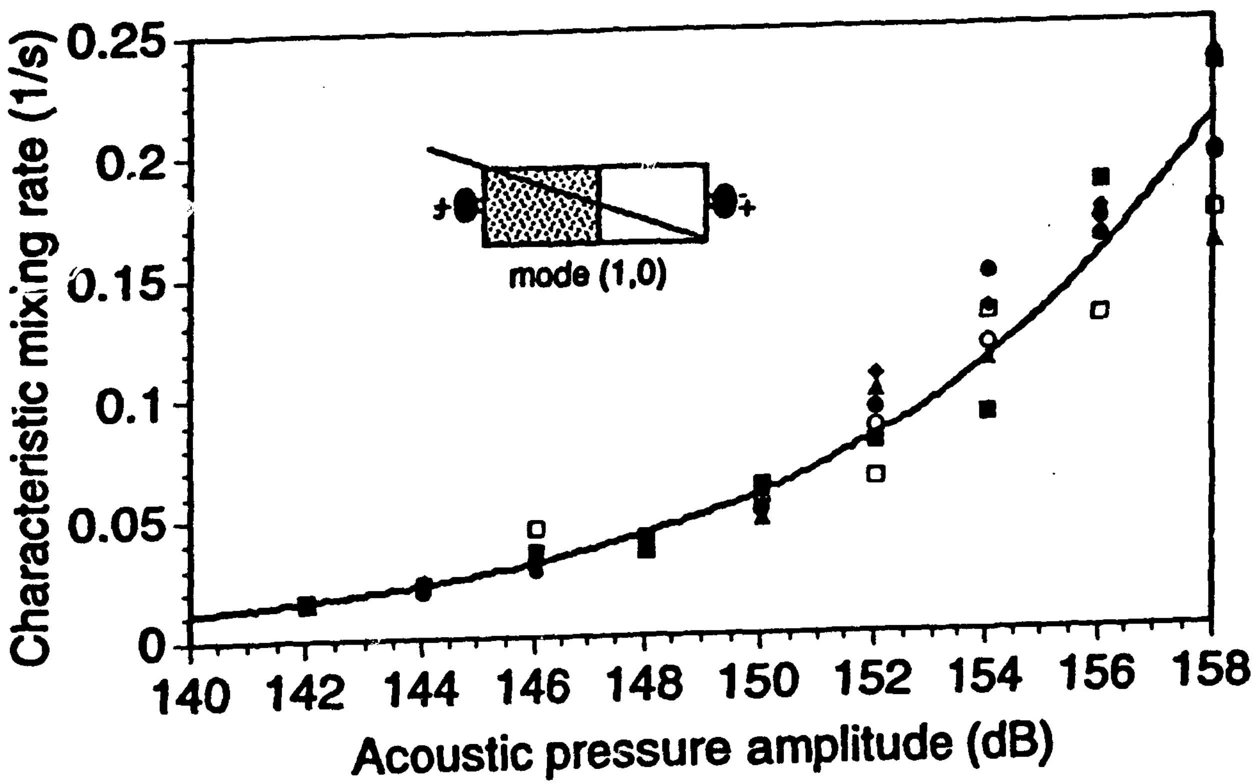


Figure 10. Characteristic mixing rate vs acoustic pressure amplitude

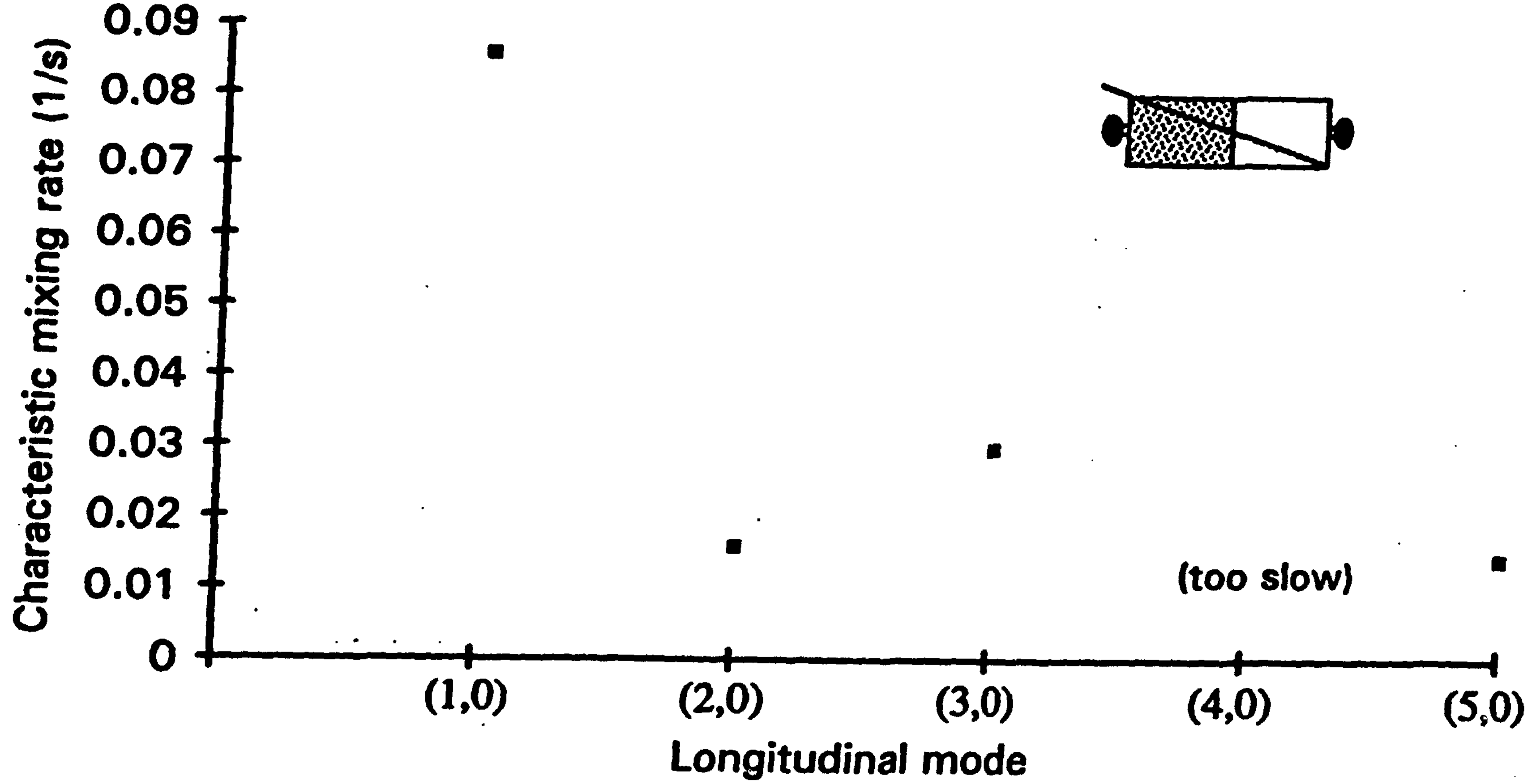


Figure 11. Dependence of mixing rate upon longitudinal mode @ 152dB

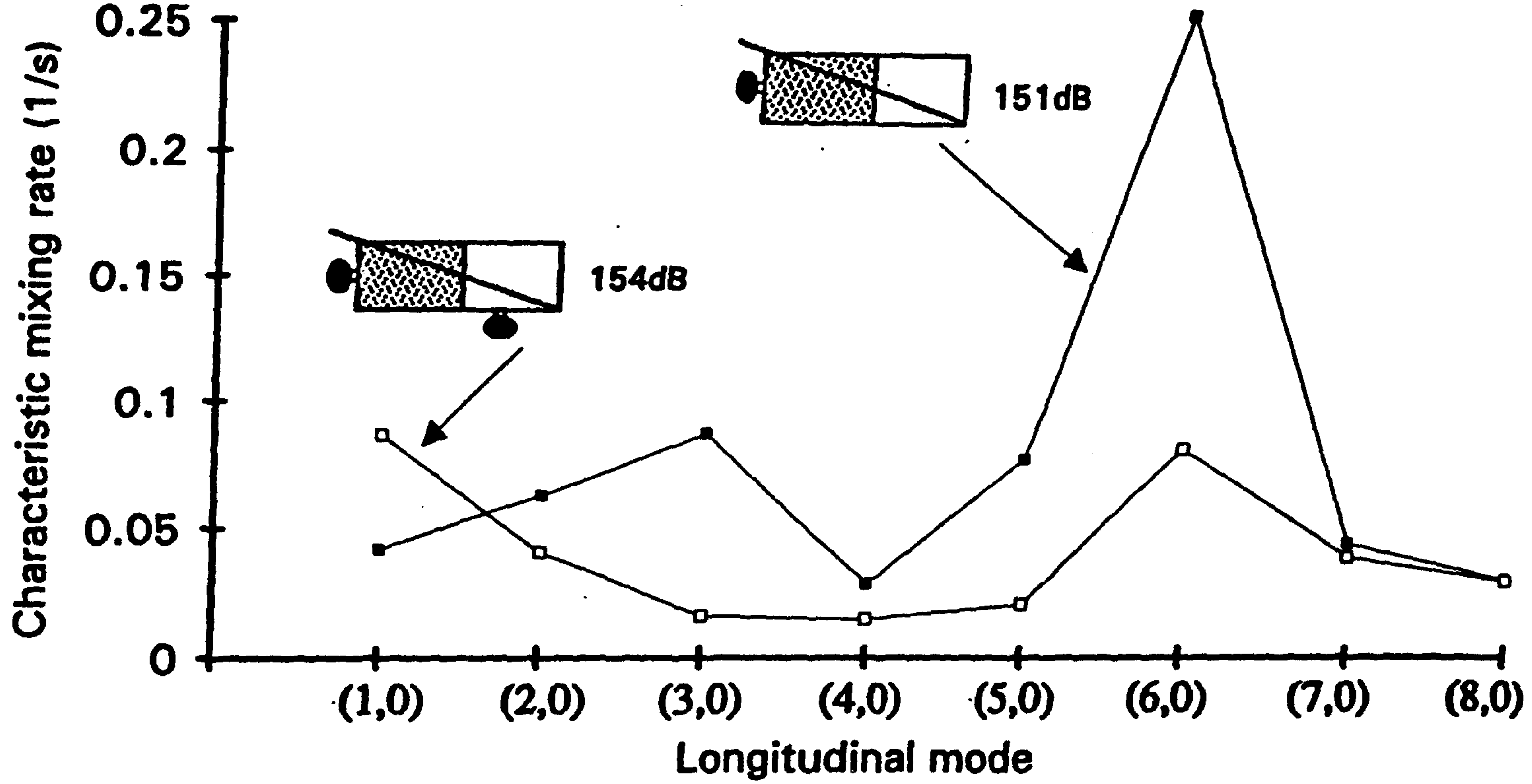


Figure 12. Comparison of mixing rate dependence upon mode in different situations

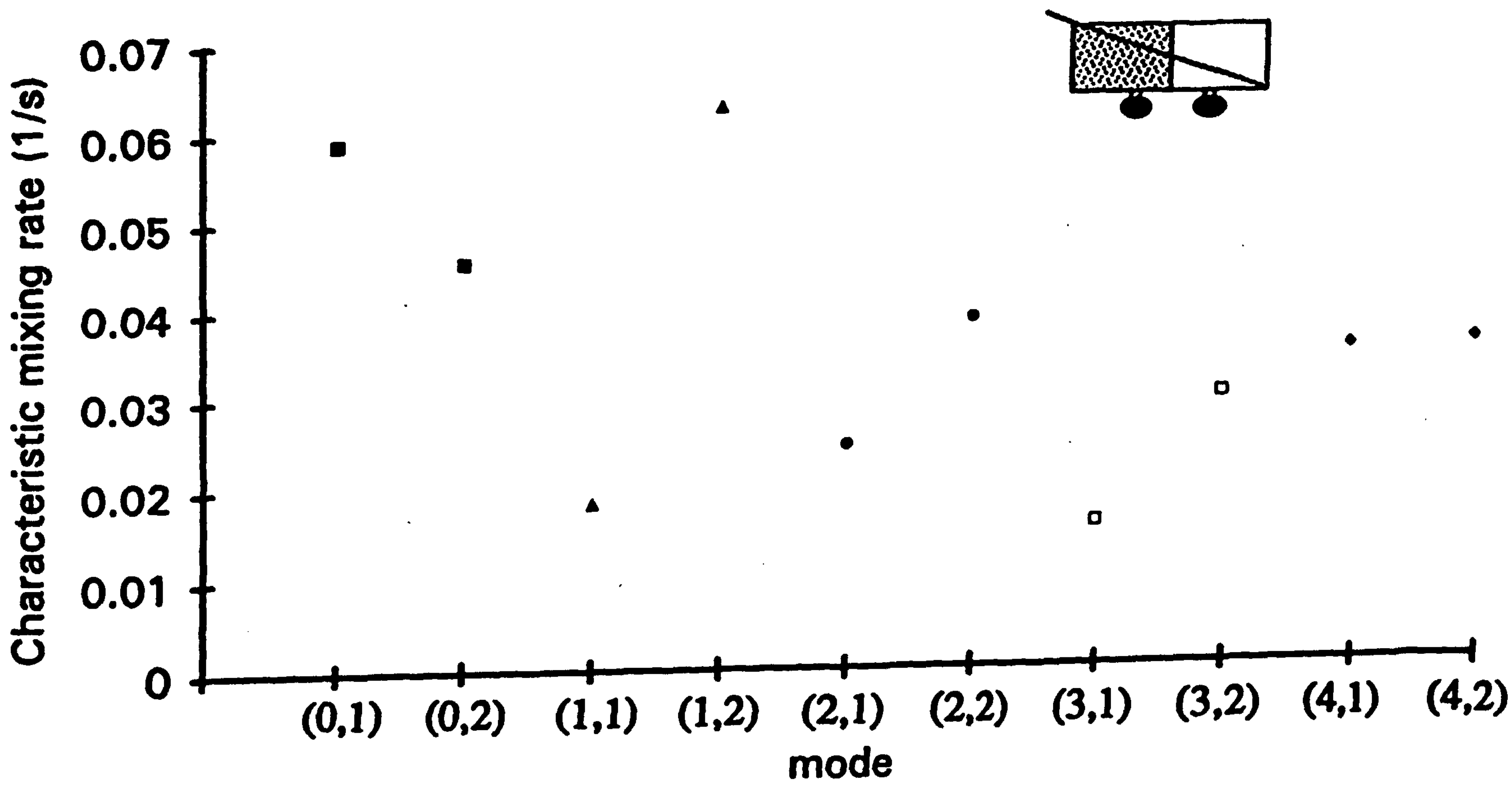


Figure 13. Dependence of characteristic mixing rate upon mode @ 148dB

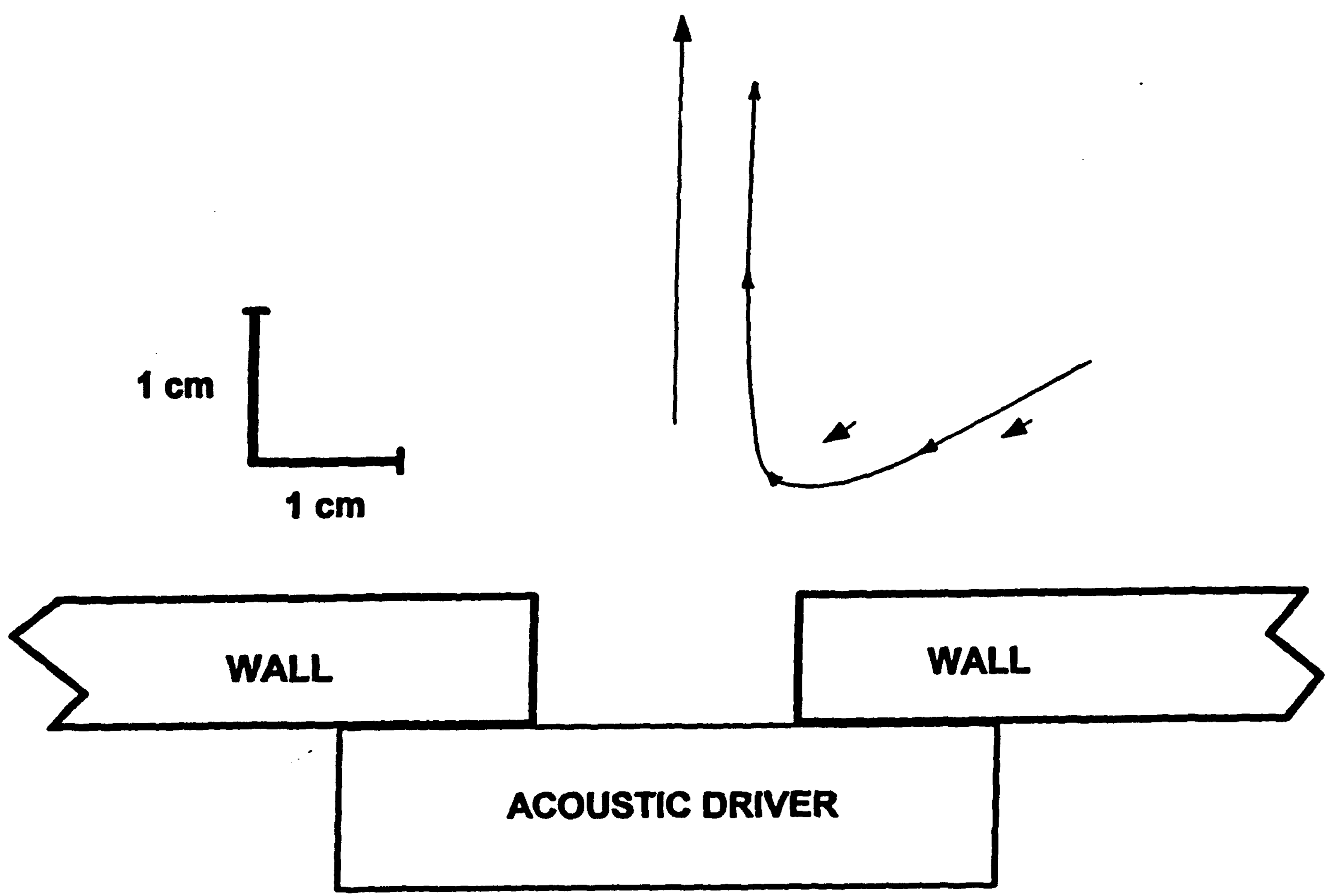


Figure 14. Mean velocity measurements and an interpolated streamline showing the streaming in the vicinity of a wall mounted acoustic driver.

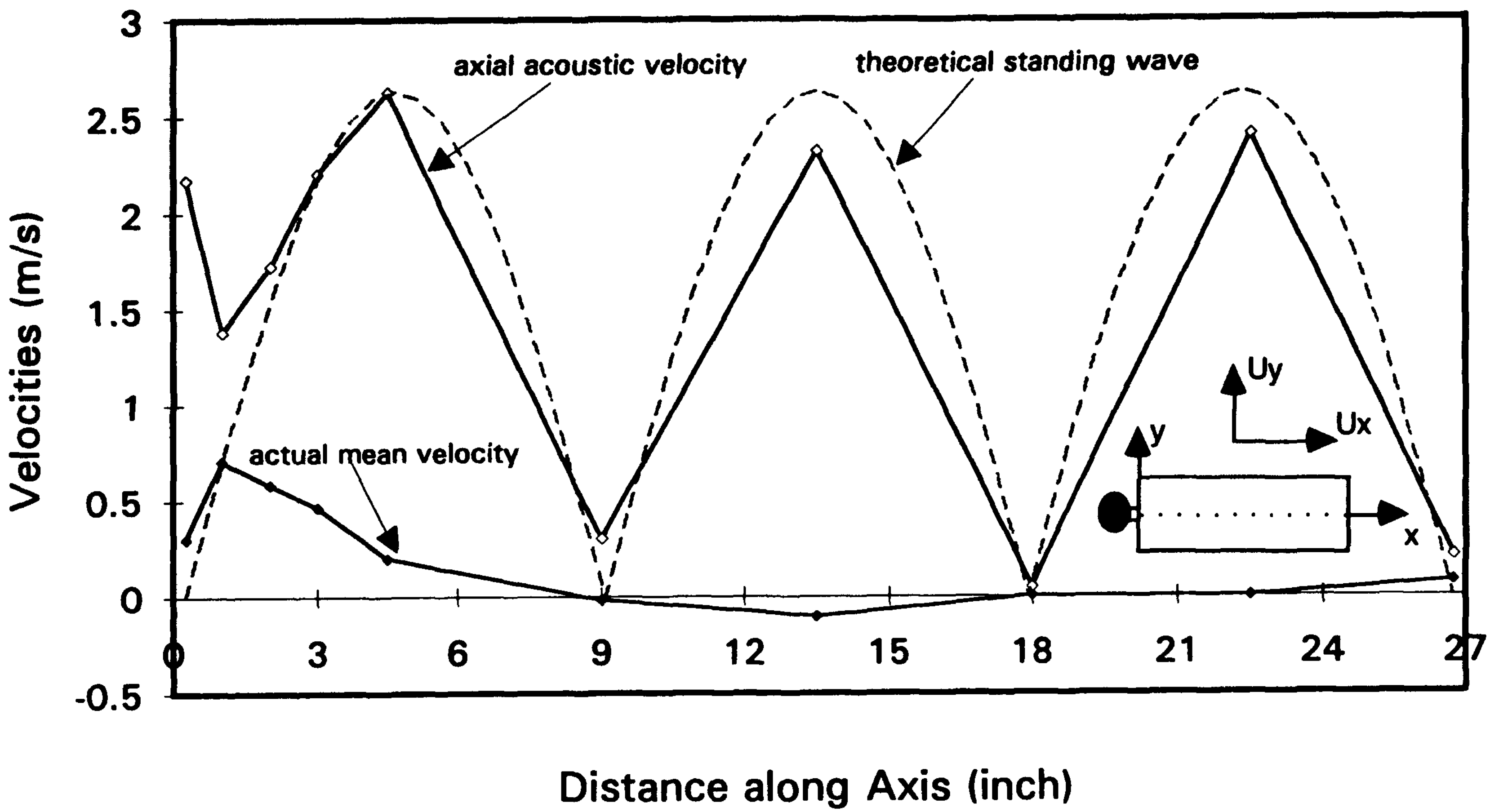
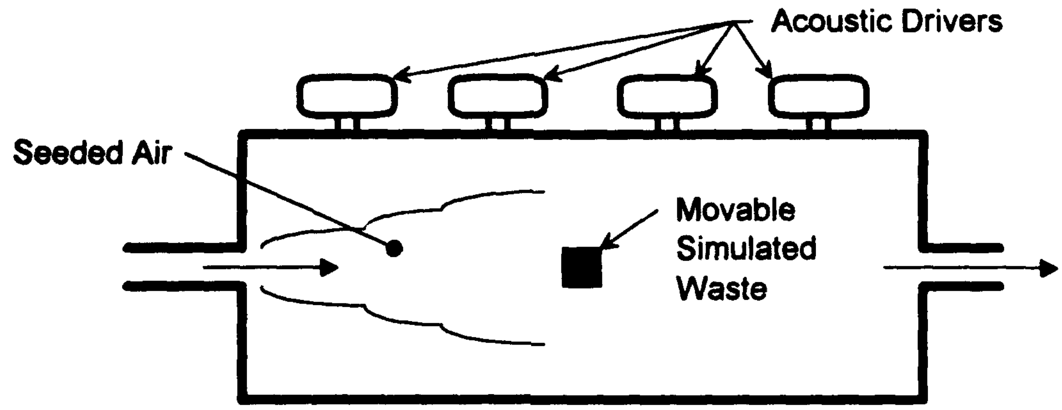
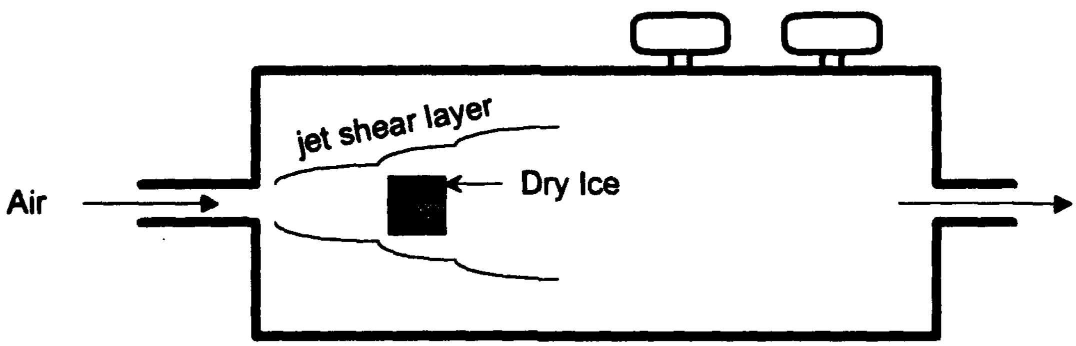


Figure 15. Dependence of mean and oscillation velocities upon distance away from the speaker with SPL=150dB frequency=758Hz at mode(3,0)



a) Flow visualization configuration.



b) Dry ice sublimation configuration.

Figure 16. Schematic of the simulated incinerator configured for a) Mie scattering flow visualization experiments and b) dry ice sublimation studies.